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Sense and Avoid Characterization of the Independent Configurable Architecture for Reliable Operations of Unmanned Systems

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Abstract—Independent Configurable Architecture for Reliable Operations of Unmanned Systems (ICAROUS) is a distributed software architecture developed by NASA Langley Research Center to enable safe autonomous UAS operations. ICAROUS consists of a collection formally verified core algorithms for path planning, traffic avoidance, geofence handling, and decision making that interface with an autopilot system through a publisher-subscriber middleware. The ICAROUS Sense and Avoid Characterization (ISAAC) test was designed to evaluate the performance of the onboard Sense and Avoid (SAA) capability to detect potential conflicts with other aircraft and autonomously maneuver to avoid collisions, while remaining within the airspace boundaries of the mission. The ISAAC tests evaluated the impact of separation distances and alerting times on SAA performance. A preliminary analysis of the effects of each parameter on key measures of performance is conducted, informing the choice of appropriate parameter values for different small Unmanned Aircraft Systems (sUAS) applications. Furthermore, low-power Automatic Dependent Surveillance – Broadcast (ADS-B) is evaluated for potential use to enable autonomous sUAS to sUAS deconflictions as well as to provide usable warnings for manned aircraft without saturating the frequency spectrum.

Keywords—small unmanned aircraft systems (sUAS); sense and avoid (SAA); detect and avoid (DAA); unmanned aerial vehicle (UAV); Automatic Dependent Surveillance – Broadcast (ADS-B)

I. INTRODUCTION

Commercial applications of unmanned aircraft operating at low altitudes are likely to increase in the near future presenting both business incentives as well as huge airspace integration challenges. The full range of these low-altitude Unmanned Aircraft Systems (UAS) operations will likely include [1] *"…those that are fully contained in uncontrolled airspace, to those that require transit across the boundary between controlled and uncontrolled airspace, and finally to those that originate and operate within controlled airspace …"* As a result, scenarios in which UAS will operate in close proximity to each other or with other users of the airspace will be increasingly common, such as in the vicinity of a terminal area.

Consequently, the ability of small UAS vehicles to sense traffic aircraft in the airspace and maintain a safe separation distance from other vehicles is a fundamental requirement to the integration of UAS into the National Airspace System. Research on sense and avoid (also referred to as detect and avoid or DAA) for small UAS has focused mostly on development of separation assurance algorithms. Published research provides very little or no validation of these systems in a real-life setting. Furthermore, available sense and avoid algorithms for small UAS are often geared towards providing traffic awareness to remote pilots to maintain well clear, but do not consider the post-conflict maneuvers required to guide the vehicle back to the original path.

This paper details the results of various tests (both simulation and flight tests) conducted to evaluate and validate the sense and avoid capability of the Independent Configurable Architecture for Reliable Operations of Unmanned Systems (ICAROUS). ICAROUS was designed as a distributed publish-subscribe software architecture to enable the easy integration of mission-specific functionality and/or sensor technologies. Presently, ICAROUS runs onboard the vehicle on a companion computer but future instantiations of ICAROUS could be directly integrated with lower-level autopilot functions. Simulation testing enabled performance evaluation against a wide variety of well-clear parameters, initial conditions, and encounter geometries. Flight testing was used to validate simulation results and demonstrate ICAROUS as a practical, usable system for real world UAS applications. Flight tests were conducted against an unmanned fixed wing aircraft to validate scenarios involving low closure rate encounters with other unmanned aircraft vehicles. A manned general aviation (GA) aircraft was used to validate the sense and avoid capability in a high closure rate scenario representative of encounters between UAS and GA aircraft in a terminal area setting.

Two additional goals of this effort were to evaluate the efficacy of a representative Automatic Dependent Surveillance-Broadcast (ADS-B) receiver for sUAS as a source of cooperative traffic surveillance for Sense and Avoid (SAA) applications and to investigate the use of reduced-power ADS-B position report transmissions for low-altitude sUAS operations. While the widespread use of ADS-B is not considered feasible for sUAS due to potential frequency congestion, low power ADS-B has the potential to enable these operations without negatively impacting the air traffic system.

To be a viable approach, ADS-B output power must be significantly reduced while maintaining the range and quality needed for small UAS operations in addition to providing useful warnings to manned aircraft. If the use of ADS-B does not provide useful alerts to manned aircraft, then there would be no justification for its use for UAS. Multiple levels of attenuated ADS-B output were tested during this effort with both sUAS to sUAS as well as sUAS to manned aircraft to evaluate low power ADS-B as a solution to this problem.

This paper is organized as follows. Section II provides an overview of existing research related to sense and avoid. Section III provides background on the ICAROUS architecture and the Detect and Avoid Alerting Logic for Unmanned Systems (DAIDALUS), which is used by ICAROUS. This section also includes background on the Minimum Operational Performance Standards (MOPS) used to evaluate ICAROUS maneuvers and on the sensors used by UAS in sense and avoid (SAA) operations. Section IV discusses methods used for simulation and testing of ICAROUS. Section V provides a detailed analysis of ICAROUS' performance with varied input parameters, and of the effectiveness of low power ADS-B. Finally, sections VI-VII provide a discussion of observed results, future work, and conclusions.

II. RELATED WORK

Collision avoidance for manned aircraft has been an area of intense research since the advent of the Traffic Collision Avoidance System (TCAS). The TCAS system was developed to provide pilots with adequate information to make decisions regarding evasive maneuvers to mitigate risk due to an intruder in the airspace [2]. The TCAS system has seen several iterations and continues to be the backbone of collision avoidance in the civil commercial aviation community. Using transponders, TCAS I provides warnings (traffic advisories) of nearby intruders in the airspace. The TCAS II system also provides resolution advisories to the pilot in addition to the traffic advisories. In case of a resolution advisory, the pilot has the final authority and is required to implement these resolutions.

The Advanced Collision Avoidance System (ACAS-X) [3], the next generation of collision avoidance algorithms, was introduced with the objective of replacing TCAS. Unlike TCAS, ACAS-X uses a model-based decision-theoretic framework where traffic resolutions and advisories are optimized using a reward function that considers the encounter dynamics. The use of a decision-theoretic framework introduces multi-dimensional lookup tables thus making its implementation as well as its verification and validation a challenging task. Verification and validation of ACAS-X resolutions is an ongoing research activity [4].

Unlike manned aircraft operating at high altitudes, small UAS have different mission dependent performance constraints. Consequently, a straightforward translation of the collision avoidance algorithms used for manned aircraft may not be applicable. Collision avoidance algorithms for small UAS need to be cognizant of various constraints such as geofences and obstacles in a low altitude airspace or an urban airspace environment. Integration of detect and avoid capability with path planning capability was discussed in [5].

For UAS, the final report of the Federal Aviation Administration (FAA) Sense and Avoid (SAA) Workshop [6] defines the concept of sense and avoid as "*the capability of a UAS to remain well clear from and avoid collisions with other airborne traffic.*" Based on this definition, the UAS Sense and Avoid Science and Research Panel (SARP) made a recommendation for a quantitative definition of UAS well clear that uses distance and time functions similar to those used in the TCAS II resolution advisory logic [7]. For large, remotely piloted UAS, the RTCA Special Committee 228 (SC-228) has developed minimum operational requirements for detect and avoid that uses SARP's well-clear definition [8]. DAIDALUS [9] is a NASA developed software that serves as a reference implementation of the minimum operational performance standards for the UAS detect and avoid concept defined in RTCA FAA DO-365. The scope of the DAA requirements detailed in DO-365 is limited to large vehicles operating in controlled airspace. These requirements are not adequate for small sUAS operating in low altitude airspace.

Several researchers have investigated the sensing aspects of collision avoidance for small UAS. Surveillance performance of sensors required to perform SAA in small UAS with emphasis on risk was considered in [10]. That work provides a mapping between surveillance performance and collision risk. An analysis of the usage of radars for sense and avoid was provided in [11]. The use of ground-based radars to perform sense and avoid in a local area was investigated in [12]. Dolph et al. [13] used cameras to visually detect intruders in the vicinity. Acoustic sensors for intruder detection have also been used in [14]. Experimental evaluation of a rudimentary sense avoid algorithm was conducted in [15]. A survey of various sense and avoid algorithms for small UAS can be found in [16].

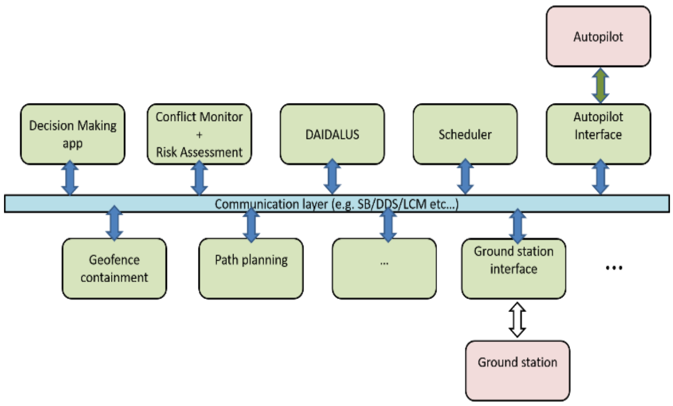

Figure 1. ICAROUS architecture

III. Background

A. ICAROUS

ICAROUS is an architecture that integrates a collection of core algorithms for path planning, geofence handling, traffic avoidance, and decision-making capabilities to enable autonomous operation of UAS [17,18]. Fig. 1 provides an overview of the ICAROUS architecture, which uses NASA's core Flight Systems (cFS) middleware. ICAROUS was designed to run on a companion computer while consuming data from an autopilot system. It monitors the autopilot system, mission performance, and other mission and safety constraints. ICAROUS assumes control of the vehicle when a constraint violation is imminent and autonomously implements resolution maneuvers to prevent conflicts and mitigate risk.

B. DAIDALUS

The sense and avoid functionality implemented within ICAROUS is provided by DAIDALUS [9]. DAIDALUS is a DAA software library available under NASA's Open Source Agreement. DAIDALUS consists of algorithms that predict well-clear violations between the ownship and traffic aircraft and provide maneuver guidance in the form of ranges of maneuvers for the ownship to maintain or regain well clear. These algorithms have been formally verified for logical correctness in the Prototype Verification System (PVS).

C. ICAROUS Resolutions for SAA

The DAIDALUS detect and avoid library is highly configurable and uses a list of parameters that govern its response to an intruder in the airspace. The present work evaluates only the lateral resolutions provided by DAIDALUS. These lateral resolutions are in the form of track guidance and require the ownship to change its heading, but not its altitude. Given the position and velocity of intruder aircraft in the airspace, DAIDALUS outputs a range of track angles that could result in well-clear violation. These outputs are a function of the initial parameter set used to configure DAIDALUS. A list of all parameters used by DAIDALUS and detailed explanation of these parameters can be found in [18] For the ISAAC test, the effects of the following parameters were investigated.

- Well-clear alerting time threshold – time before predicted well-clear violation to start avoidance maneuver
- Well-clear distance threshold (DTHR) – horizontal distance to be maintained between ownship and traffic aircraft
- Well-clear time threshold (TTHR) – This time threshold is related to the Modified Tau (TAUMOD) threshold used in the TCAS alerting logic and it provides an estimate to time of closest point of approach.

The time when a resolution maneuver is computed depends both on the alerting time threshold and the well-clear thresholds. The sum of these time thresholds approximates the time prior to closest point of approach when the resolution maneuver is computed. In the present work, these times are varied in a way that their sum remains constants.

When a conflict occurs, ICAROUS selects an avoidance maneuver from the guidance maneuver ranges computed by DAIDALUS and autonomously commands the autopilot to execute it. ICAROUS also constantly checks to see if the turn to intercept the original flight plan would cross a conflict track heading. ICAROUS initiates the return to path maneuver only when the vehicle is clear of a well-clear conflict and when returning to the original mission no longer results in loss of separation. Return to path can be implemented in multiple ways depending on the mission. The vehicle could return to the next waypoint in the current flight plan or, alternately, it could return to the point on the flight plan where it initially deviated to avoid loss of separation. For this work, return to path is treated as returning to the next waypoint in the current flight plan.

D. Sensors for SAA in Small UAS

The limited payload carrying capability of small UAS poses significant restrictions on the type of onboard traffic surveillance sensors that can be used for SAA. Currently available off-the-shelf sensors suitable for SAA applications on small UAS include vehicle-to-vehicle communication devices and ADS-B for cooperative traffic, and airborne radars, LIDAR, vision-based sensors (cameras), and acoustic sensors for non-cooperative traffic. Ground based radars can also be used as a traffic surveillance source. Different sensor technologies have inherent capabilities and limitations, as well as varying performance metrics and operational constraints. ICAROUS was designed to be sensor agnostic, and configurable to adjust to different sensor performance and uncertainty ranges. Prior work conducted as part of the UTM Technology Capability Level 3 (TCL3) flight tests studied the suitability of vehicle to vehicle communication devices for sense and avoid [19].

This work specifically focuses on the use of the pingRX ADS-B receiver manufactured by uAvionix [20] for providing intruder position data (UAS-UAS and GA-UAS). The ping module is very light weight and integrates with a Pixhawk/ArduPilot flight controller [21].

The pingRX is considered to be representative of the types of ADS-B receivers that could be used for sUAS applications. Internal vehicle communication of ADS-B data is sent via the ADSB_VEHICLE message of the MavLINK protocol [22] containing information about aircraft call sign, ICAO address, GPS coordinates (latitude and longitude), altitude, and vehicle velocity. The ISAAC test relies on ADS-B technology to assess the performance of ICAROUS autonomous SAA capability since its performance and accuracy exceed those of other sensor technologies. However, the of use ADS-B-based SAA for sUAS is usually not considered to be an acceptable solution since the increased volume of transmissions could overload and impair existing systems. M. Guterres et al. [24] found that the main factors that would impact ADS-B functionality are UAS fleet density and transmission power. To allow UAS fleet density to increase, reduced power ADS-B must be explored or another frequency spectrum be allocated for UAS use. Much research remains to be done to understand the potential applicability of low-power ADS-B for sUAS and its impact on the air traffic system.

IV. METHOD

A software in the loop (SITL) simulation capability was developed to study performance metrics of a large number of SAA configurations. The SITL integrates ICAROUS with a high-fidelity quad-rotor simulation model and an autopilot system through a MavLINK protocol. ICAROUS guidance commands are executed by the SITL simulator and relevant metrics are computed to characterize its performance. A wide range of SAA configurations were run, including well-clear distance thresholds ranging from 300 to 2000 feet, and alerting time thresholds ranging from 0 to 25 seconds. Preliminary analysis of the results was used to guide and down select the SAA configurations used in the ISAAC flight test. Flight test results validate simulation tests and further characterize the performance of the algorithms with real sensor data, winds, and turbulence, amidst various factors such as transmission latency, ADS-B packet drop outs and GPS errors

A. Flight Test Approach

A DJI S1000 octocopter with an ArduPilot autopilot system was used as the ICAROUS equipped ownship aircraft for these flight test. An onboard companion computer connected to the autopilot hosted the ICAROUS software that communicated with the autopilot via the MavLINK protocol. This setup is illustrated in Fig. 2.

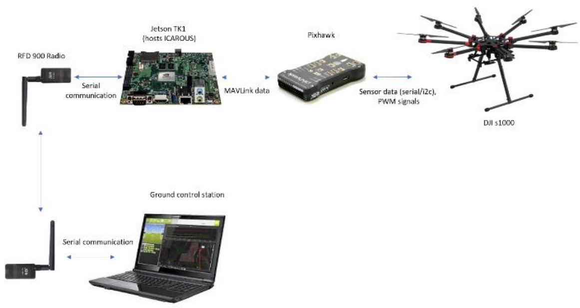

Figure 2. Hardware setup

The flight test was conducted in two phases. For the first phase, UAS-to-UAS encounters, the intruder aircraft was a Tempest Unmanned Aerial Vehicle (UAV) [23]. For the second phase, UAS-to-GA aircraft encounters, the intruder was a Cirrus SR-22. Scenarios included encounters with two different geometries, head-on and at 90-degree angle. All flight tests were conducted at the Beaver Dam Air park located near Smithfield, VA, in the vicinity of multiple airports. As a result, ADS-B signals from multiple commercial planes were also present during testing.

Flight safety requirements imposed several constraints on the encounter geometry whose impact warrants an explanation. Since both UAS had to be within visual-line-of-sight of the operators at all times, it was challenging to set up the test conditions with larger well clear distances and with encounters with high closure rate (as those involving a GA). Since in those cases the encounters start when the aircraft are in close proximity to the well-clear boundary, late detections are likely to occur. In those cases, the ownship may not have enough time to avoid the specified well-clear.

1) Flight Test Setup

The flight test comprised two phases: Phase 1 included UAS vs UAS encounters and Phase 2 UAS vs GA aircraft encounters.

a) Phase 1: UAS vs UAS

Fig. 3 illustrates the flight plans of the two aircraft for a head on encounter. On the left (shown in blue) is the flight path of the fixed-wing intruder (Tempest) aircraft. On the right (shown in yellow), is the flight path of the ownship (DJI S1000) vehicle. The intruder aircraft flew counter clockwise flights which generated a direct head-on collision hazard for the ownship. A 500 foot boundary was established to separate the vehicles and mitigate risks of mid-air collisions.

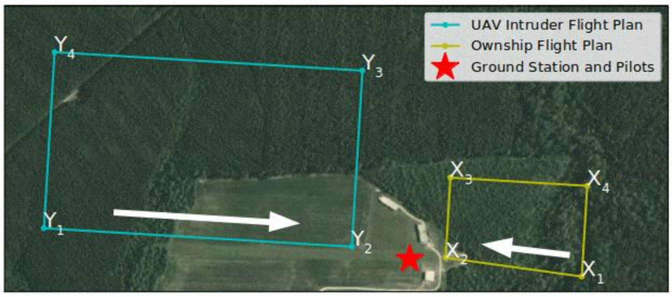

Figure 3. Head on encounter UAV flight plans

These flight paths are chosen so that the vehicles are 500 feet apart at the closest point if no autonomous traffic deconfliction maneuvering is performed. The two vehicles are set up to operate at roughly the same altitude. The intruder aircraft maintains a constant speed of 20 m/s throughout all encounters. The ownship maintains a constant speed of 10 m/s. Thus, the relative closure rate between the two vehicles for the head on encounters is 30 m/s (approximately 60 knots). This rate of closure is considered to be representative of nominal sUAS to sUAS encounters, but higher closure rates may be possible. Flight paths are chosen to maximize the likelihood of a predicted conflict between the two vehicles. In Fig. 3, a well-clear conflict should occur between the two vehicles during the southernmost leg of the flight plan.

Flight paths for the 90-degree encounter are shown in Fig. 4. Once airborne, the Tempest intruder aircraft is flown up to its cruising altitude and its autopilot is engaged so that it continues to fly the programmed rectangular pattern. After the Tempest is established on its flight plan, the octocopter is launched and manually flown to waypoint X_1. Once at waypoint X_1, the octocopter loiters until the encounter can be initiated.

The encounter is initiated by engaging the Pixhawk's autopilot, triggering it to fly the programmed flight plan. An encounter initiated too soon can result in the octocopter completing the flight leg between waypoints X_1 and X_2 before observing a well-clear conflict. Similarly, an encounter initiated too late can result in the intruder completing its leg ahead of the ownship or the traffic deconfliction maneuver being initiated prior to reaching steady-state cruise conditions. An encounter initiated at the right timing results in the two vehicles approaching each other head on, leading to a well-clear conflict. Several trials were done to establish the timing to produce a well clear. The distance of the intruder from waypoint Y_1 can be used to time encounters consistently. The exact timing depends on the well-clear radius, alerting time of the detect and avoid configurations used by ICAROUS, and prevailing winds and needs to be adjusted throughout testing. Fig. 5 shows an example of detect and avoid response from a head on encounter.

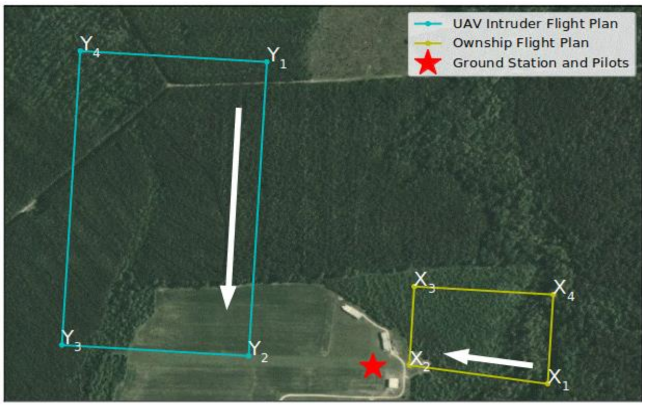

Figure 4. 90-degree encounter UAV flight plans

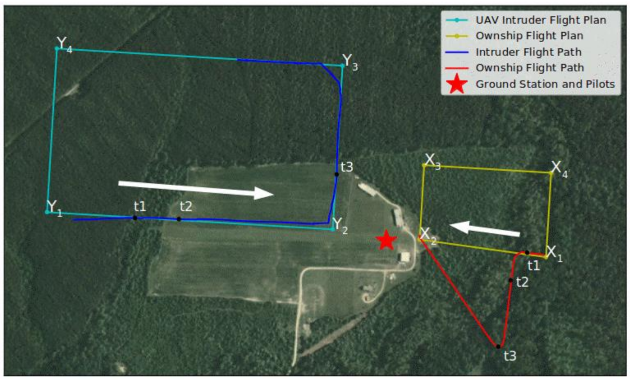

Figure 5. Example of DAA maneuver

The octocopter's autopilot is engaged at point X_1, when the corresponding position of the intruder is near point Y_1. Once the ownship's autopilot is engaged, it starts accelerating towards its next waypoint, X_2. At point t_1 a well-clear conflict is predicted and ICAROUS assumes control of the ownship's autopilot. ICAROUS issues guidance commands to direct the ownship away from the well-clear conflict. ICAROUS continues this heading guidance until it is safe to return to the mission. The computation of the return to path maneuver is discussed in Section III. At point t_3, the ownship is safe to return to the original mission and ICAROUS starts guiding the aircraft towards the next waypoint, X_2.

b) UAS vs GA

The flight paths for the manned aircraft are shown in Fig. 6. Note that for tests involving a well-clear radius of 2000 feet, the flight path of the GA aircraft is offset by 1000 feet. This is mainly to restrict the deviations of the UAS to be within 1000 feet in the pilot's line of sight. In these tests, the GA aircraft maintains a constant airspeed of 100 knots. The ownship maintains a constant speed of 10 m/s. Note that this setup results in a relative closure rate of 60 m/s in head-on encounters. Timing for encounter initiation is similar to the flight tests with a UAV intruder. Following the GA plane position on an ADS-B monitor helps to get the timing right.

Figure 6. Flight plans for manned intruder

2) Tests with Geofences

Flight tests also included scenarios with a simple keep-out geofence added either to the north or south of the ownship's flight plan to force deviations in specific directions. These geofences can be static, i.e. known before flight, or dynamic, i.e., provided during flight (also referred to as “dynamic restrictions”). In this setup, the ownship is expected to deviate away from the geofence while executing a traffic avoidance maneuver. These additional conditions were included to demonstrate ICAROUS integrated SAA-geofence containment capability.

3) Reduced Power ADS-B

During the flight tests described above, three levels of UAS ADS-B output power were tested:

- 40 Watts (full power)
- 1.3 Watts (15 decibel attenuation)

- 0.4 Watts (20 decibel attenuation)

The different output power levels were produced by adding a 50 Watt RF attenuator to the ADS-B transmitter on the UAV intruder (Tempest). By swapping out the attenuator between flights, different transmission powers were achieved. The output power for each scenario is estimated based on the 40 Watts nominal output of the antenna.

B. *Flight Test Conditions*

The ISAAC test conditions were designed to evaluate the impact of different well-clear volumes and alerting times used by the core avoidance logic. Table 1 enumerates the test conditions for both the UAS-UAS and UAS-GA encounters.

TABLE 1. TEST CONDITIONS

Intruder Type	DTHR	Alerting Time (s)	TTHR (s)	Encounter Type	Runs
GA	1000	20	0	Head On	3
GA	1000	10	10	Head On	2
GA	1000	20	0	90 deg	1
GA	1000	10	10	90 deg	3
GA	2000	20	0	Head On	2
GA	2000	10	10	Head On	3
GA	2000	0	20	Head On	3
GA	2000	20	0	90 deg	3
GA	2000	10	10	90 deg	3
GA	2000	0	20	90 deg	3
UAS	1000	20	0	Head On	6
UAS	1000	10	10	Head On	2
UAS	1000	0	20	90 deg	3
UAS	2000	10	10	90 deg	5

Each condition is repeated several times (runs) for different well-clear configurations. As explained earlier, the encounter geometries were constrained by the flight safety requirements as well as the test site limits. Hence, only 1000 and 2000 feet of horizontal separation were tested. Also, at most 20 seconds of total alerting time + TTHR time were tested. The choice of alerting time (i.e., time at which maneuver guidance is first computed prior to well-clear violation) and TTHR (i.e., well-clear time threshold based on aircraft closure rate) values was informed by simulation results.

Only lateral avoidance maneuvers are considered for this effort. Lateral maneuvers require the ownship to change heading, but not altitude, to maintain separation with the intruders. In both phases of flight testing, the intruders do not react to the ownship and continue on their respective flight plans. Additional maneuvers are being explored as part of ongoing work.

Fig. 7 summarizes the impact alerting time, well-clear radius, and time threshold on the horizontal miss distance at the closest point of approach during the different encounters.

In the graphs, a horizontal miss distance smaller than the horizontal well-clear radius indicates a loss of separation, while a separation distance greater than the well-clear radius indicates a conservative avoidance maneuver.

V. RESULTS

A. *ICAROUS Performance*

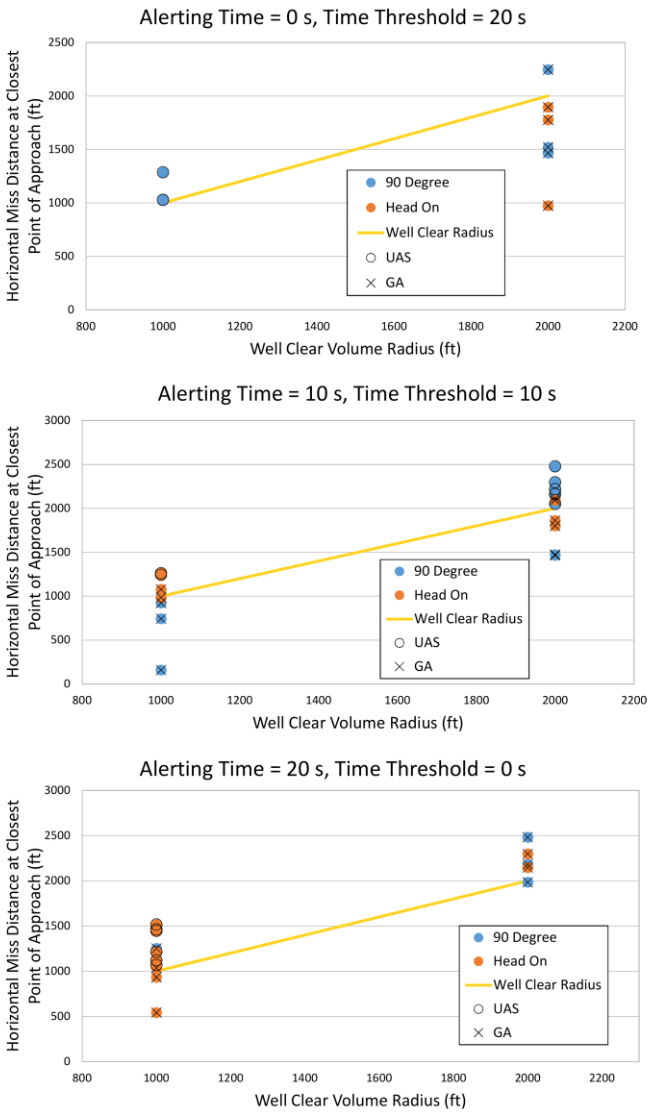

Figure 7. Horizontal Miss Distance for all Horizontal Distance, Alerting and Threshold time test parameters

There were 42 successful runs, 16 UAS-UAS and 26 UAS-GA encounters. The UAS-UAS encounters experienced no losses of separation regardless of horizontal separation or combination of alerting and threshold time parameters used. This may indicate that for low closing speeds (< 30 m/s) the configurations chosen are safe and possible overly conservative.

Of the 26 UAS-GA encounters there were 16 losses of separation, with intrusion distances ranging from 14 feet to 1000 feet. The data shows that all but 1 of the losses was related to the test site constraints and the choice of parameters that proved to be insufficient for the closing speeds of the GA-UAS encounters. In those cases, the SAA equipped UAS was initialized too close to the well clear boundary or in some cases, already in a loss of separation. However, the data seems to indicate that the alerting time component is more consequential than TTHR resulting in fewer losses of separation. The most successful set of runs corresponds to 2000 feet of horizontal separation and 20 seconds of alerting time.

Analysis of the remaining case shows an anomaly in the system, possibly related to an autopilot condition that caused the UAS to slow down as the encounter progressed. After the UAS reaches the commanded speed of 10 m/s in autonomous mode, it unexpectedly and abnormally decreases the speed to 0.53 m/s. The GA aircraft is flying in the direction of the UAV at a speed of 54.5 m/s (106 knots). According to configuration parameters, maneuver guidance is computed by ICAROUS 21 seconds prior to CPA when the aircraft have a horizontal separation of 3763 feet (1147m). Given the performance limits of the UAS, ICAROUS does not find a track resolution for the UAS. It does find ground speed and vertical resolutions, but they are not currently integrated into the decision-making logic. The UAS, still in autonomous mode, slowly accelerates. The first track resolution autonomously implemented by the UAS is computed by ICAROUS 16 seconds prior to CPA. At this time the aircraft have a separation of 2827.73 feet (862m). The UAS does not have enough time to avoid a loss of separation and passes 758.68 ft (231 m) from the GA aircraft.

B. *ADS-B Sensor Performance*

1) *ADS-B for UAS Sense and Avoid*

The pingRX ADS-B receiver used in these tests provides a simple practical way to incorporate ADS-B data into UAS sense and avoid operations and is considered to be representative of future devices that could be used for commercial UAS operations. In our tests, the pingRX was able to successfully decode greater than 90% of the ADS-B messages sent by the intruder UAV aircraft at full transmission power (40 W). Slightly better results were seen from the GA plane, with greater than 95% of ADS-B messages successfully received. Since this analysis was performed using telemetry logs from the ownship ground station, some of these missed updates could be attributed to lost packets in the telemetry link, which would not affect the amount of ADS-B data available to ICAROUS. However, analysis shows that fewer than 2% of packets were dropped over the telemetry link. In addition, packets lost due to drops out of the telemetry link would be assumed to affect all ADS-B transmission power levels and aircraft types (UAS vs GA).

When using the pingRX, parameters such as ADS-B range filter and maximum number of ADS-B targets passed on to the autopilot system need to be carefully selected for each application. Otherwise, messages from the target intruder aircraft may be dropped due to the pingRX being overloaded with aircraft in the general vicinity. During testing it was observed that the pingRX was receiving ADS-B data from aircraft more than 50 miles away. The pingRX also performed less reliably when subjected to large vibrations in flight. Periods of high vibration appeared to coincide with gaps in ADS-B reception of up to 10 seconds. These issues should be understood and accounted for before using ADS-B and the pingRX for safety critical UAS operations.

ICAROUS performed successful SAA maneuvers using ADS-B input from the pingRX for more than 30 flight tested encounters. The range of full power ADS-B has no effect on small UAS operations, as the lookahead time and alerting time parameters in ICAROUS limit the monitored range to be much smaller than the actual range of ADS-B reception. The few encounters where ICAROUS failed to maintain well clear were not caused by ADS-B errors, but were due to well-clear definition and timing parameters that were inappropriate for the scenario being tested. For example, alerting time was too small to alert ICAROUS of an incoming aircraft with enough time to complete the required maneuver.

These tests demonstrate the use of ADS-B for sUAS in scenarios involving both unmanned and manned aircraft. Any ADS-B receiver needs to be carefully integrated and tested before use in safety critical applications.

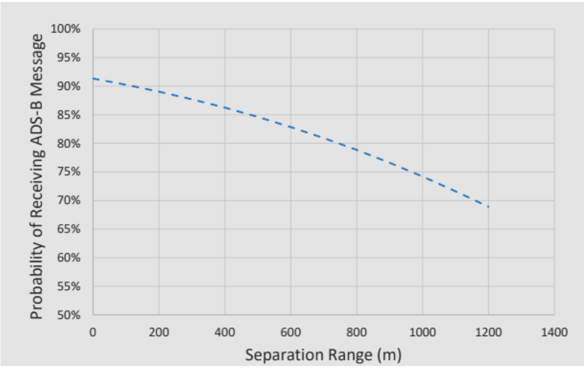

Figure 8. Probability of pingRX successfully receiving a 0.4 Watt output ADS-B message, dependence on separation range

2) *Reduced Power ADS-B*

ICAROUS performed successful detect and avoid maneuvers at three different ADS-B output power levels. Even with the lowest power (0.4 Watt) signal, 83% of ADS-B messages were received by the pingRX unit within the 0-1200 meters separation range tested. This reception rate proved sufficient for ICAROUS avoidance maneuvers within this range.

Fig. 8 shows a logistic regression between the probability of ADS-B message reception and separation range between the two vehicles. The regression shows how increasing distance between the two vehicles reduces the probability that a transmitted ADS-B message will be successfully received by the ownship. Each received message is associated with the distance between the two vehicles at the time the message was sent, based on ownship GPS position and intruder ADS-B data. The missed messages are estimated based on the standard once per second broadcast rate, and associated with the approximate distance between the two vehicles at the time of expected transmission. For the full power signal, the range between vehicles does not significantly affect the probability of message reception ($p = 0.125 > 0.05$) within the tested range. For the 1.3 Watt signal, the range significantly affects the probability of message reception ($p = 0.015 < 0.05$). For the 0.4 Watt attenuated signal, the effect is highly significant ($p < 0.0001 < 0.05$). This is expected for reduced power transmissions.

A 70% reception corresponds to an expected 2-3 seconds between messages. As the vehicles get closer together, this reception rate increases. These tests indicate that these message reception rates are sufficient for UAS avoidance maneuvers, even at the greatly reduced transmitting power. M. Guterres et al. [24] concluded that UAV ADS-B transmit power within 0.01-0.1 Watts, coupled with a fleet density less than 5 UAVs per square kilometer is required to maintain acceptable ATM message reception rates of greater than 80%. The current test evaluated only single aircraft and testing of multiple aircraft in higher-density operations is required to establish the actual upper power limit. The lowest output power tested in this effort was 0.4 Watts which is above the suggested criteria yet provides minimum required performance. It is feasible that the sensitivity of the pingRX unit could be improved, but that was beyond the scope of the current effort. Lower transmission powers that fall within this range should be tested in future efforts. In addition to achieving adequate performance for UAS to UAS applications, results for UAS to GA aircraft were also adequate. Observations from the manned GA SR-22 aircraft revealed that for the mid-power level the position of the intruder Tempest aircraft was observed more than 15 miles away. When the Tempest ADS-B power output was attenuated to ~400 mWatts, its location was observed consistently by the GA aircraft from at least 8 miles away. This distance is equivalent to approximately 4 minutes warning time for the GA aircraft.

VI. Discussion

A successful maneuver to avoid a well-clear conflict is largely a function of the performance of the aircraft and position communication link. Factors such as the speed and turn rate of the vehicle play a significant role in maneuvering to avoid an approaching intruder and also affect the required range of position communication link performance. Consequently, careful consideration of the parameters chosen for well clear is crucial. These parameters must be chosen to handle the fastest intruder in a given airspace.

The phase 1 flight tests with the Tempest aircraft resulted in closure rates of 30 m/s during head on encounters and 22 m/s during the 90-degree encounters. With a turn rate of 10 degrees/second, and a top speed of 10 m/s, the octocopter was able to maneuver fast enough to avoid a well-clear violation defined by the configuration parameters.

Proper selection of parameters depends on many factors including intruder speed, desired separation radius, and ownship limitations in turn rate and speed. Conservatively chosen parameters will reduce the risk of a well-clear violation, but consume more time and fuel as the ownship executes long maneuvers that are not necessarily required to maintain safe separation. On the other hand, if parameters are chosen to maximize efficiency, the ownship may lose well clear during encounters with higher speed vehicles. A well-clear definition and parameters must be chosen carefully for each application and be based on actual assessments of the risk of vehicle collisions. Values evaluated herein were considered nominal and appeared very conservative to ground observers. The results of these tests characterize ICAROUS' performance under different configurations and inform the effective selection of parameters for future operations.

VII. Conclusions and Future Work

A. *Development of ICAROUS*

The ICAROUS capability for autonomous SAA was designed as a distributed software architecture based on well-established communication protocols and developed using formally verified SAA algorithms. ICAROUS has been undergoing extensive simulation evaluations as well as flights to evaluate its performance in real flight conditions.

The ISAAC flight test was designed to explore the performance of the autonomous SAA functionality in conflict encounters of a UAS with both another UAS and a GA aircraft. The flights were conducted on days with mild wind conditions. Performance was measured in terms of horizontal miss distance as a function of well clear horizontal separation, alerting, and threshold times.

Results from this test indicate that ICAROUS autonomous SAA capability was very effective in maintaining separation between two UAS in mild wind conditions, with closing speeds not exceeding 30 m/s, and for all combination of alerting and threshold times and distance parameters used. Results from the UAS-GA encounters were impacted by the constraints of the ISAAC test design that did not allow some of the test conditions to be initialized properly, causing late detections and losses of separation. However, within the limits of the test conditions, results seem to indicate that at closing speeds in the order of 100 knots an alerting time of 20 sec and a separation threshold of 2000 feet was effective for all tested encounters.

The ISAAC test was the first flight test designed to shed light over this complex and wide-ranging problem and, clearly, there remains work to be done. Future flight studies need to explore the parameter space beyond the ISAAC limits and to characterize the performance of other sensor technologies for SAA to determine if it can support such applications.

B. *Attenuated ADS-B Output for UAVs*

These tests demonstrate that low powered, 0.4 Watt, ADS-B transmission is a practical option for UAV to UAV applications. The output powers tested provided sufficient quality and range for ICAROUS to perform consistent detect and avoid encounters. Reduced power should decrease the risk of frequency congestion that would interrupt normal ADS-B use, but may require lower transmit powers than tested here. In addition, further work is needed to understand the potential impact of high density low-power transmissions on ground receivers and multilateration systems.

Future tests should assess the 0.01 to 0.1 Watt transmission power suggested by [24]. Tests should also be conducted over larger separation distances and examine the impact that several UAVs transmitting at this low power would have on ATM ADS-B operations, especially the impact of a fleet of UAVs operating at or near an airport.

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